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Radial Flow and Oxygen Plasma

Distribution in the Kronian Magnetosphere

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Abstract

The appearance of significant and possibly dominant amounts of oxygen ion plasma in the middle and outer magnetosphere of Saturn is considered. If diffusion were the primary mode of transport, nitrogen ions from Titan would be the dominant ion since oxygen ions would be lost by charge exchange with the neutral hydrogen cloud. Therefore, a radial convective flow system, driven by the azimuthal divergence caused by failure of the planet to impose rigid corotation is investigated for incompressible flow. We find that such a flow regime can maintain the supply of oxygen plasma to the trans-Rhea region and is qualitatively consistent with observed flow patterns.

INTRODUCTION

Radial velocities, both inwards and outwards, have been observed in the magnetosphere of Saturn [Lazarus and McNutt, 1983]. It has also been found that the mass of the heavy ion in the outer magnetosphere is more likely to be 16 amu than 14 [Richardson, 1986). It has been shown by Eviatar et al. [1983] that if the transport of ions from the inner icy satellites, i.e., oxygen and other water vapor debris and the transport of nitrogen from Titan depend on radial diffusion, the presence of the neutral hydrogen cloud will prevent substantial amounts of O^+ from reaching the outer magnetosphere and the dominant ion at L = 15 or more, should be N^+.

In this letter, we shall consider a possible alternative means of providing O^+ plasma to the middle and outer magnetosphere from the sources located at Rhea's orbit and inward. The mechanism we propose is direct flow out of the inner magnetosphere.

Flow Model

We start with the steady-state continuity equation

$$\frac{\partial n}{\partial t} = -\nabla\cdot(n\vec{v}) - \sigma v_{\phi} n_{H} n = 0. \tag{1}$$

In this equation, n is the oxygen ion number density, $\underline{v}$ is the plasma flow vector, $\underline{v} = (v_r, v_\phi, v_z)$, σ is the O^+ - H charge exchange cross section and n_H is the number density of neutral hydrogen in the outer magnetosphere cloud, where charge exchange with neutral hydrogen is assumed to be the dominant loss mechanism. The incompressibility of the flow ($\nabla\cdot\underline{v} = 0$) leads to the equation:

$$v_L \frac{\partial n}{\partial L} + v_\phi\left(\frac{\partial n}{\partial \phi} + \sigma n_H R_S n\right) = 0 \tag{2}$$

where $L = r/R_S$, i.e. the distance at which a field line intersects the equatorial plane, expressed in Saturn radii.

It has been shown recently [Eviatar and Richardson, 1986) that the azimuthal flow in the inner magnetosphere of Saturn is significantly subcorotational and lacks azimuthal symmetry. From this we shall proceed to calculate the parameters v_L and v_ϕ required for the solution of equation 2. For the moment, we shall ignore the vertical component of the flow and express the incompressibility in cylindrical coordinates thus,

$$\frac{\partial(Lv_L)}{\partial L} = -\frac{\partial v_\phi}{\partial \phi} \tag{3}$$

For large values of L, $\frac{\partial v_\phi}{\partial \phi} \to 0$ and $v_\phi \to R_S \Omega L$ where Ω is the rotation rate of Saturn.

These conditions will be satisfied by: $\frac{\partial v_\phi}{\partial \phi} = -\alpha' R_S \Omega (\frac{L_o}{L})^p$ in which α is a positive function of ϕ that has a minimum shortly after local noon and a maximum shortly after local midnight, which corresponds to the local time profile of ionosphere plasma density [Kaiser et al., 1984). The value of the exponent p can, in principle, be determined from the latitude dependence of the ionospheric conductance and the radial dependence of the mass loading rate (vid. Eviatar and Richardson, 1986 and discussion below). In our notation $\alpha' = \frac{d\alpha}{d\phi}$. This leads to

$$v_\phi = R_S \Omega \left(L - \alpha \left(\frac{L_o}{L} \right)^p \right) \tag{4}$$

We may then integrate equation 3 to obtain

$$L v_L = L_o v_L(L_o) + \frac{\alpha' R_S \Omega L_o}{(p-1)} \left(1 - \left(\frac{L_o}{L} \right)^{p-1} \right) \tag{5}$$

We impose the boundary condition that $Lv_L \rightarrow 0$ as $L \rightarrow \infty$, which implies that

$$v_L = - \frac{\alpha' R_S \Omega}{(p-1)} \left(\frac{L_o}{L} \right)^p \tag{6}$$

It is implicit in the above that $p > 1$. We also note that the direction of v_L will depend on the sign of α', which can be determined from the observations. If the azimuthal velocity depends on the conductivity in such a way that $\alpha'<0$ in the morning sector, as we assume, we predict that there will be outflow in the morning sector and inflow in the afternoon and evening sector.

We may now return to solve equation 2 for the density distribution. As the equation stands, an analytical solution is most difficult, for the variables are not separable. For the moment, let us assume azimuthal uniformity of density, i.e. $\frac{\partial n}{\partial \phi} = 0$ and obtain the simple radial equation:

$$n = n(L_o)\exp\left(-\int_{L_o}^{L} \left(\frac{v_\phi}{v_L}\right)\sigma n_H R_S dL'\right). \tag{7}$$

In the morning semicircle, $v_L > 0$, $L > L_o$, $n \to 0$ for $L \to \infty$ and in the afternoon and night semicircle, $v_L < 0$, $L < L_o$, $n \to 0$ for $L \to \infty$. Thus the boundary condition for large L is satisfied in both sectors. Our final expression for the density as a function of L is:

$$n = n(L_o)\exp\left[\frac{\sigma R_S n_H (p-1)}{\alpha'} \left(\frac{L^{p+2} - L_o^{p+2}}{(p+2)L_o^p}\right) - \alpha\left(L - L_o\right)\right] \tag{8}$$

COMPARISON WITH OBSERVATIONS

The trajectories of both Voyager spacecraft were such that they entered the magnetosphere in the early afternoon, went around the planet on the dusk ansa and then left on the night side. As a result, we have flow and density data primarily in the afternoon and evening sectors, with only a period of a few hours available in the post midnight sector.

In Figure 1a we show the dipole L values sampled by Voyager 1 as a function of local time. Figures 1b, 1c and 1d show the corotation fraction, $v_\phi/R_S\Omega L$, the non-azimuthal fraction $(v_r^2 + v_z^2)^{1/2}/R_S\Omega L$ and the radial velocity in km/sec respectively, all as functions of local time as observed by Voyager 1. The sector of local time traversed by the Voyager 2 spacecraft was too small to provide data of relevance to this study on radial flow in the middle and outer magnetosphere.

We note that for Voyager 1, the speed was near full corotation from 1700 local time (LT) on through the evening sector with the spacecraft localized between the orbits of Dione and Tethys. During the early afternoon, the corotation fraction dropped sharply, there were significant nonazimuthal components and the radial velocity dropped from large positive (outward) values to small negative (inward) values at about 1330LT and 1430LT. These figures were obtained by means of the velocities given by Richardson [1986]. Details of the derivation and uncertainties are given therein. We may attribute these events to passing the noon conductivity maximum and the crossing of the L-shells of Rhea and Dione. The appearance of slowly increasing inward flow from approximately 2000LT to a maximum value of over 20 km/sec at 2300LT is reasonably consistent with the general features of the model described above. The decrease in corotation fraction and the intensification of radial flow at 2300LT appear to be associated with the crossing of the L-shell of Tethys. At about 0100LT on day 318 the spacecraft crossed the L-shell of Dione very near the ring plane. The crossing appears to be associated with a sharp drop in corotation fraction which has been attributed to mass loading of matter sputtered from Dione [Eviatar and Richardson 1986] and with a switch to outward flow in conformity with the predictions of our model.

Quantitative evaluation of equation (8) depends on obtaining reliable values of α, α' and p, none of which are readily available from the data. Nonetheless, we may compare the dropoff in O^+ density represented by equation (8) with that computed for the case of pure diffusive transport by Eviatar et al.

[1983]. For a diffusion coefficient varying as L^3 and normalized by the low energy charged particle (LECP) results at the orbit of Rhea [Krimigis et al., 1981], Eviatar et al. [1983] found that the oxygen ion density would drop off as L^{-24}, which would correspond to a depletion by a factor of $3 \cdot 10^{-7}$ between 8 and 15 R_S. For p = 2 which corresponds to the case of Σ_p being proportional to L and dM/dt being proportional to L^{-1} [Eviatar and Richardson, 1986] where Σ_p is the ionosphere Pedersen conductance and dM/dt the mass loading rate in the magnetosphere, $\alpha \sim 1/2$, $\alpha' \sim -1/2$, $\sigma = 1 \cdot 7 \cdot 10^{-15}$ cm^2 [Stebbings et al., 1960], $n_H = 20$ cm^{-3} [Broadfoot et al., 1981], L = 15 and $L_o = 8$, we find

$$\frac{n}{n_o} \approx .93 \qquad (9)$$

Although equation (9) is indeed a very rough estimate of the degree of depletion, the qualitative conclusion is firm, i.e. that not only are the middle and outer regions of the magnetosphere significantly contaminated by O^+ from the inner satellites, but in view of the higher densities in the source regions near the icy satellites, we may expect O^+ to be the dominant ion in the mantle region.

DISCUSSION

We have investigated the apparent anomaly in the charge to mass ratio inferred from plasma observations (PLS) in the middle and outer magnetosphere of Saturn. While the proximate source Titan should supply N^+ plasma and the neutral hydrogen cloud can effectively block the advection by radial diffusion of O^+ from the tori of the icy satellites [Eviatar et al., 1983], most spectra analyzed in the region between 14.5-17 R_S have shown better fits to an ion of mass 16, presumably O^+ [Richardson, 1986].

In order to explain this phenomenon, we have had recourse to the radial flows reported by both Lazarus and McNutt [1983] and Richardson [1986]. Under the assumption of incompressibility, we have shown that the deviations from rigid corotation caused by mass loading and low ionospheric conductance [Eviatar and Richardson, 1986] give rise to a radial flow directed outwards between shortly after local midnight and shortly after local noon and inwards for the rest of the diurnal cycle. Integration of the steady-state continuity equation under the assumption (admittedly _ad hoc_ and unjustified) of azimuthal symmetry in the O^+ distribution, leads to an expression for the radial variation of O^+ density which predicts that about 90% of the density at 8 R_S will be present at 15 R_S. While this cannot be regarded as a definite quantitative result since many of the parameters involved are very poorly known, if at all, it indicates qualitatively that radial flow is more effective by several orders of magnitude than diffusion in transporting oxygen through the charge exchange sink posed by the neutral hydrogen cloud. The higher densities in the source region make domination of the plasma composition by O^+, in the region that one might expect to be dominated by N^+ derived from Titan, most plausible.

We have compared the predictions of our model with Voyager 1 PLS observations of velocity components plotted against local time. While the data cannot be construed to conform rigorously to our model, they appear to be generally consistent with its broad conclusion.

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Figure Caption

Figure 1. a) Dipole L-values, b) corotation fraction, c) non-azimuthal component normalized to rigid corotation, and d) radial velocity component in km/sec, all plotted against local time.

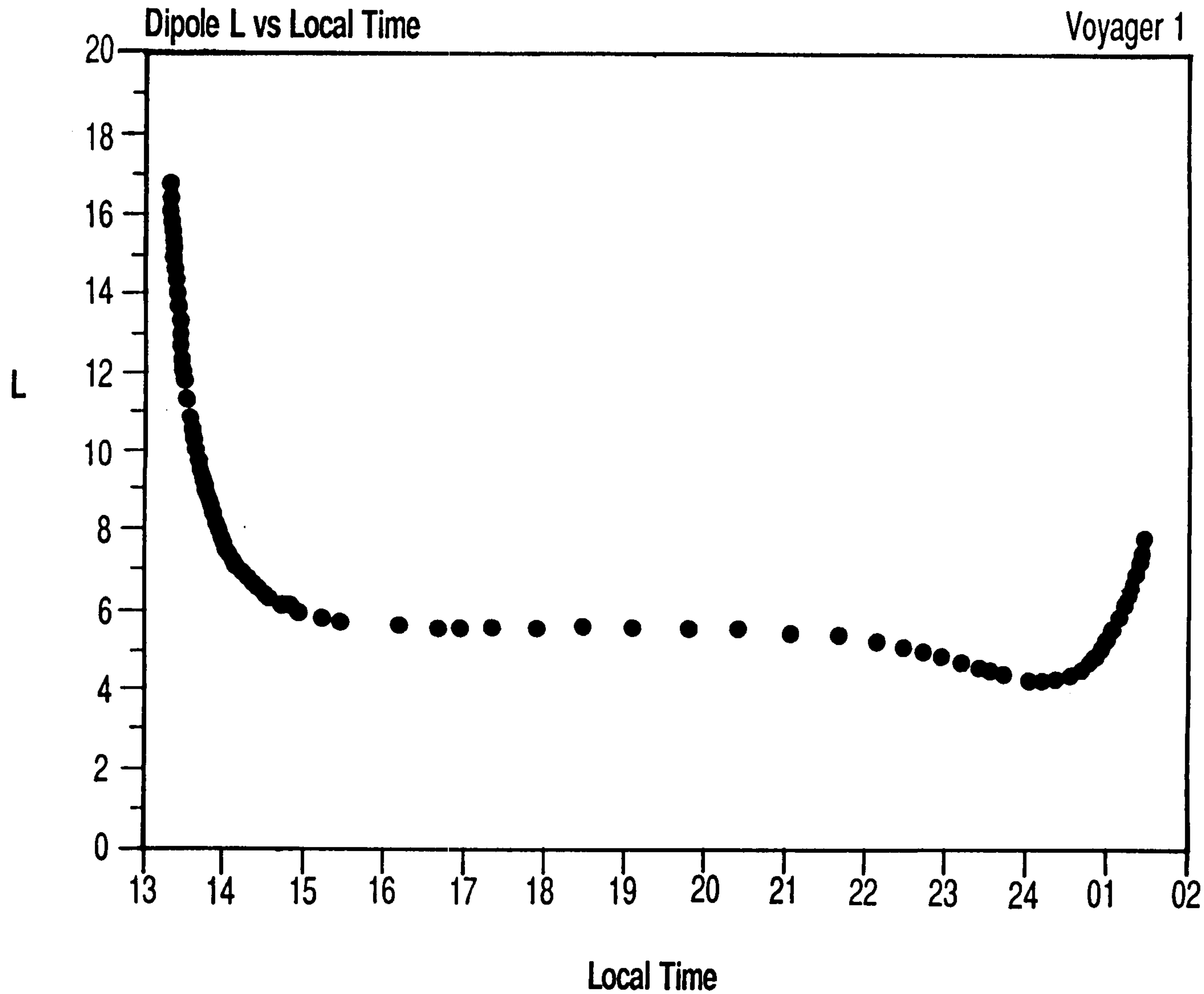

Dipole L vs Local Time
Voyager 1
L
20
18
16
14
12
10
8
6
4
2
0
13
14
15
16
17
18
19
20
21
22
23
24
01
02
Local Time

Figure 1a

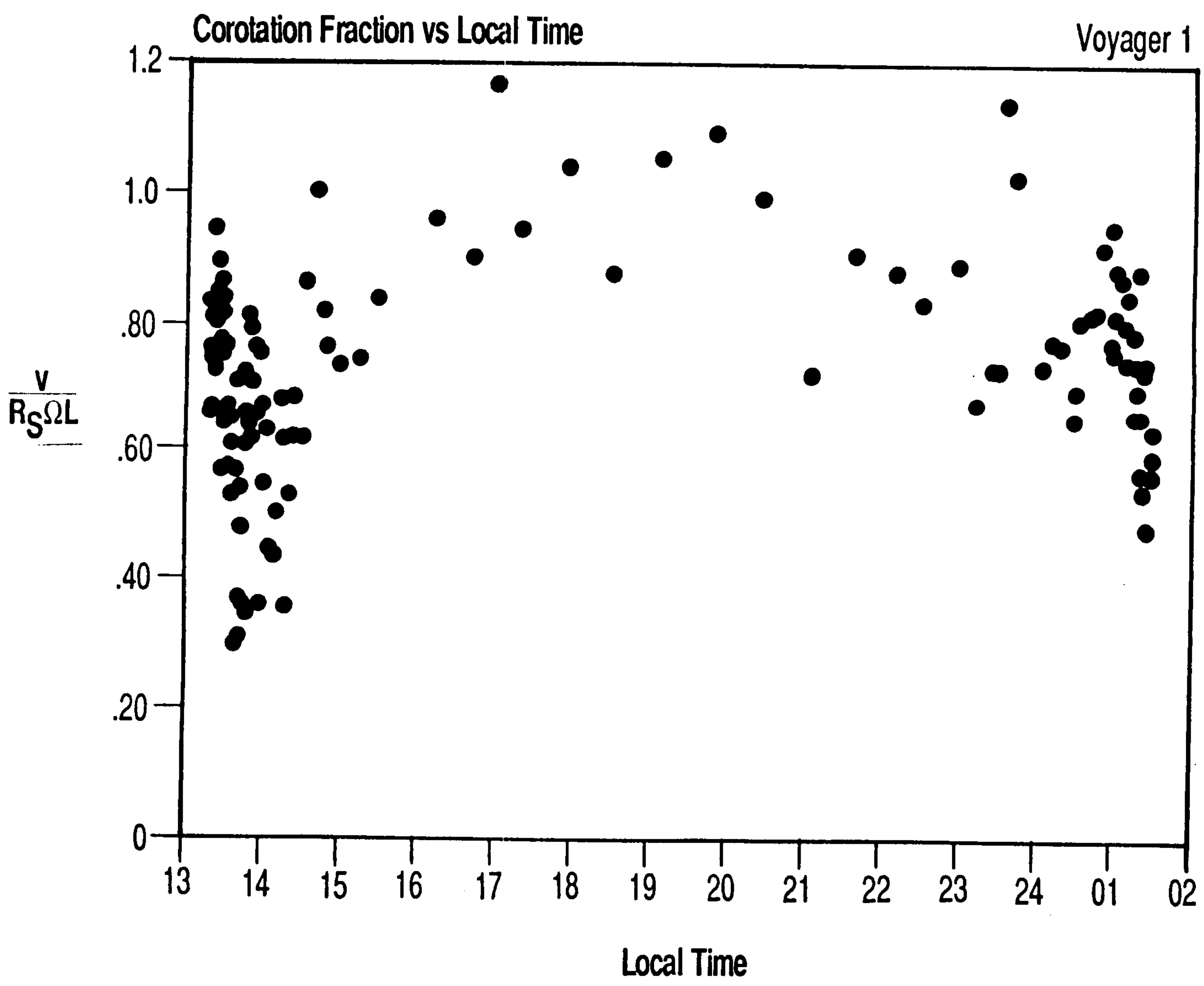

Corotation Fraction vs Local Time
Voyager 1
1.2
1.0
.80
.60
.40
.20
0
$\frac{V}{R_S \Omega L}$
13
14
15
16
17
18
19
20
21
22
23
24
01
02
Local Time

Figure 1b

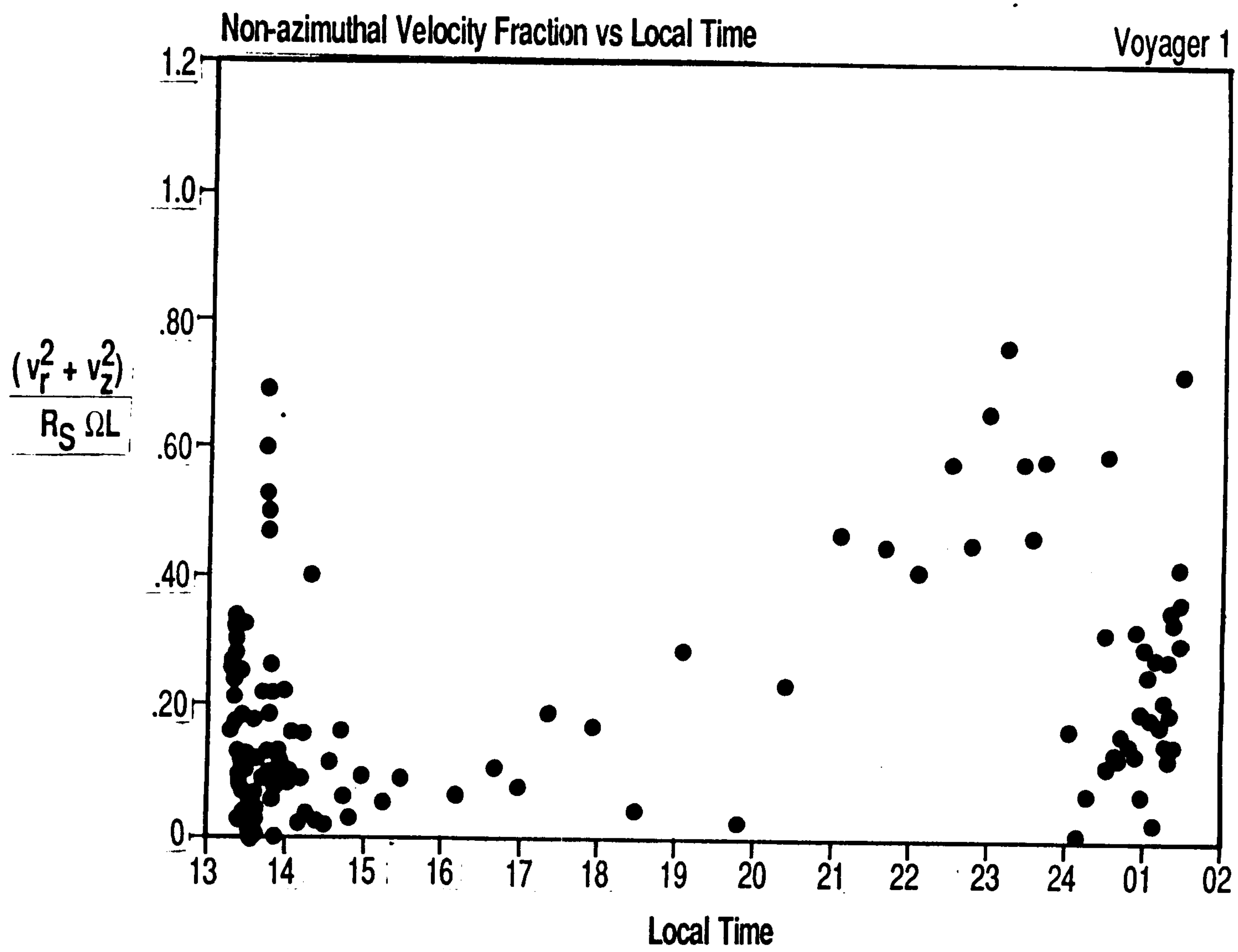
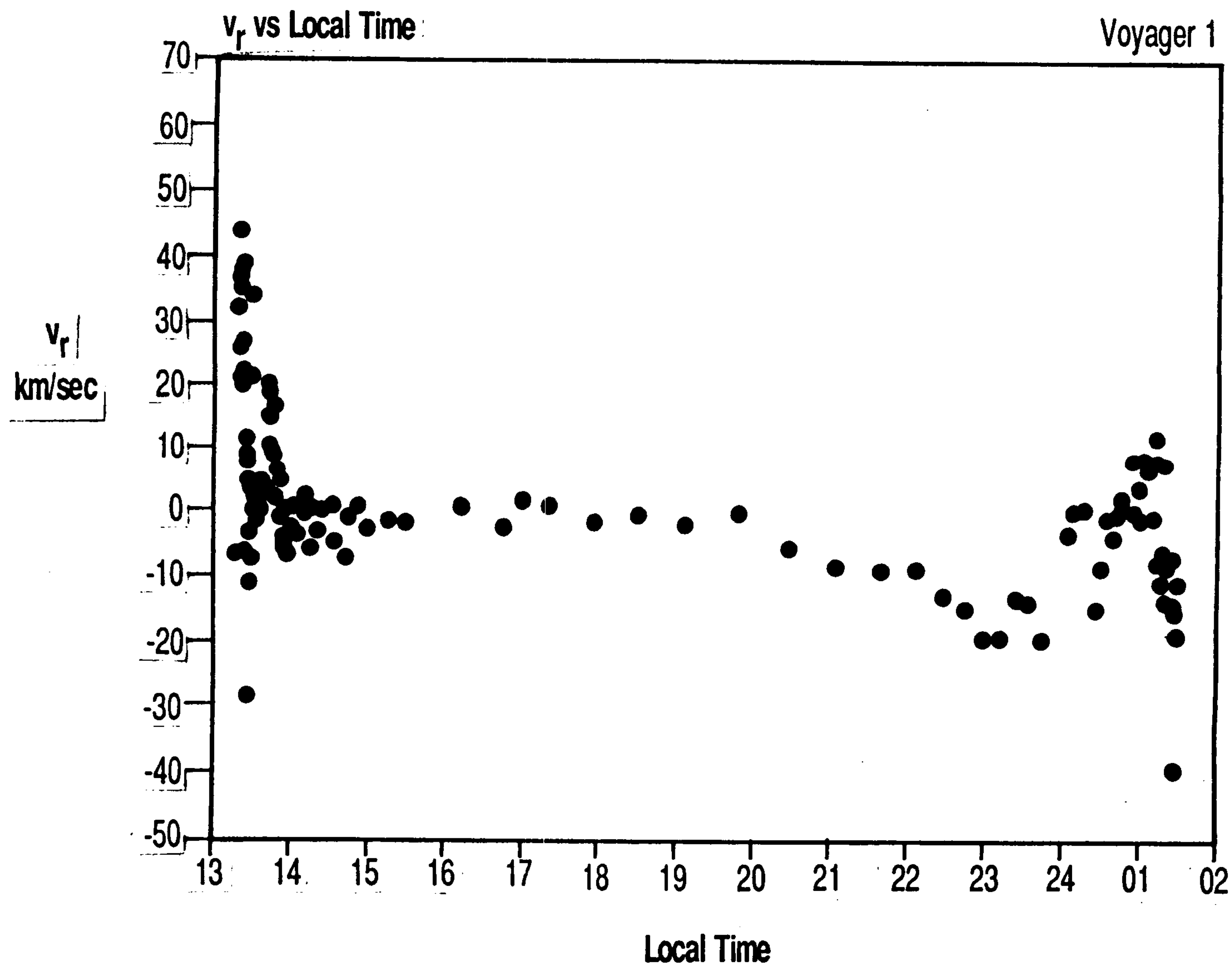

Non-azimuthal Velocity Fraction vs Local Time
Voyager 1
$\frac{(v_r^2 + v_z^2)}{R_S \Omega L}$
1.2
1.0
.80
.60
.40
.20
0
13
14
15
16
17
18
19
20
21
22
23
24
01
02
Local Time

Figure 1c



v_r vs Local Time
Voyager 1
v_r km/sec
70
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
13
14
15
16
17
18
19
20
21
22
23
24
01
02
Local Time

Figure 1d